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Static and Fatigue Strength of Linear Textile Products

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Abstract
This publication is a review of the work directed or inspired by the late Professor Andrzej Włochowicz in comparison to the current state of knowledge, and developed by his colleagues as an expression of memory and recognition of the contribution that he made to research on the strength of linear textile products. The article describes issues related to the fatigue strength of yarns. An analysis of literature related to the development of research on fatigue strength was carried out, and quantities describing load cycles and selected cases of periodically variable states of loads are presented. The article attempts to systematise certain problems related to the fatigue of textile materials. The body of the article presents the state of knowledge as well as the manner and the methods of assessment of the fatigue strength of textile materials.

Key words: *static strength, fatigue strength, textile product, yarns, fibres, stress cycles, Wöhler's diagram, Weibull's distribution.*

Introduction

The fatigue of a material is a phenomenon of breaking, i.e. fracture of the body due to loads variable over time [3].

The notion of the fatigue of material (metals) was most likely introduced by J.V. Poncelet. In the middle of the last century femenological fatigue tests were introduced by A. Wöhler. The constant increase in theoretical and experimental fatigue-themed research accompanies continuous technological progress in material engineering, the construction of machines and vehicles, and most of all in aircraft and spacecraft. The interdisciplinary nature of the textile industry causes that materials and polymers are used in designing machines and equipment for a growing range of applications. Special textile products are more commonly used in the military industry, automotive industry and aviation. These materials are expected to have special mechanical properties, for which classical theories and research methods of static strength are insufficient. The requirements for modern textile materials are often compared to those for metal or steel materials.

In the case of the variable stress of textile materials, even if its maximum value does not exceed the value of the yield strength, this may cause local microfractures in laden material after some time. In the case of composite materials for designing machines or steel products, fractures may develop over a period of time (propagation of fracture fissure) and end with a sudden brittle fracture (without previous permanent deformation of the whole element).

As for textile materials, assessment of the fatigue of material is extremely complex due to the variety of constructions and structures.

In real conditions of using the product, loads acting on structural elements are often of a variable as well as steady (sinusoidal) or unsteady (random) nature over time. Such loads are called variable loads, and stress corresponding to them is defined as variable (***Figure 1***). Variable loads cause a number of complex physical phenomena in a material, depending on the values of the load and number of cycles. A large variety of these phenomena and their accumulation lead to the weakening and ultimately damage of an element. Damage caused in such a way is called the fatigue of a material, and variable loads which led to such damage are called fatigue loads.

The first works in the scope of the fatigue strength of materials began to appear about 170 years ago, focussing on the relationship between load and fatigue life. Since then, a lot of scientific publications discussing the phenomenon of fatigue have appeared. However, no effective method of fatigue life estimation which would take into consideration all aspects investigated by scientists has been developed. This phenomenon is examined for a number of aspects such as material, shape of the subject, type of load and even the state of stress [32]. In some cases, mechanical stresses are compounded by significant thermal stresses, which cannot

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be avoided, e.g. at the time of starting-up and shutting-down of equipment or in the cooperation of two elements of different thermal expansion. In a number of elements, we deal with a multiaxial state of stresses, while the components of these stresses do not occur phase-consistently. In practice, we deal with very different stress passes of random nature resulting from varying exploitation conditions. Fatigue is the result of lots of changes taking place in differently loaded parts of equipment in which, depending on the time and the value of the load, an element is damaged as the final result.

Material loads are usually of complex nature because multiaxial states of load generate spatial stress and deformation states. The complex nature of fatigue processes forced the need to search for methods and tools useful in the process of predicting the fatigue life. Lots of hypotheses might be found in literature enabling the reduction of a complex, spatial state of stresses to a uniaxial one [32, 49]. The criteria of multiaxial fatigue related to those hypotheses might be divided in terms of the physical nature of the parameter influencing the damage of an element into stress-related, displacement-related and energy-related (stress- and displacement-related).

Methods based on the stress-related record are used mostly in the scope of the high-cycle fatigue strength of materials, whilst those based on the displacement-related record are used primarily in the low-cycle scope. Energy-related methods are used both in the case of a small and large number of cycles. It is impossible to distinguish one universal criterion in the form of a multiaxial criterion of fatigue that could be used for all types of materials due to their diversity and continuous development.

One of the main purposes of research in the field of the fatigue life prediction of textile products is the development of methods to estimate strength already at the design stage. Thanks to analyses carried out on the basis of experimental research as well as with the use of calculations and simulations based on a computer model, it is possible to predict fatigue in an early phase of the life of a product. Even more often, numerical calculation methods are also used in predicting the fatigue strength of textile products.

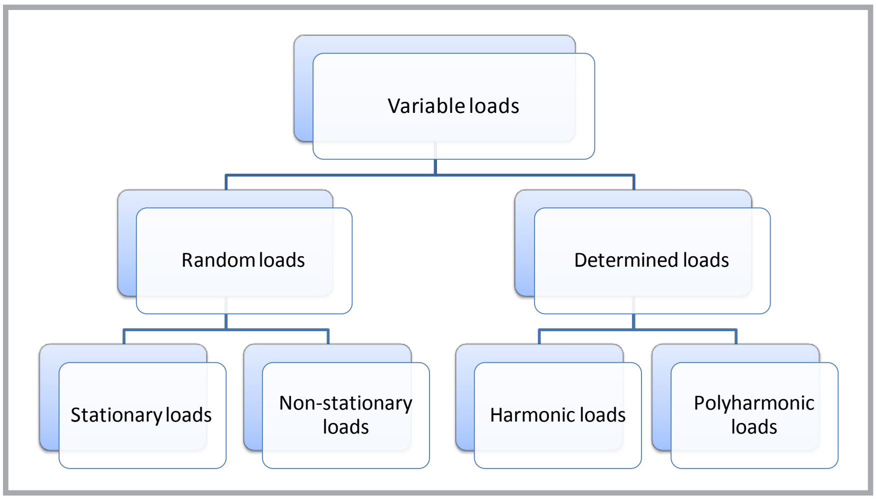


Figure 1. *Variable loads classification [26, 27].*

The fatigue phenomenon of materials appears both in the engineering industry and light industry. With the development of materials science and technology of manufacturing, new materials with specific physical and chemical properties are being developed, as a result of which it is possible to develop models allowing to estimate the fatigue life of materials with greater precision [49].

The work analyses literature on the subject matter in the scope of fatigue strength assessment methods of textile products as well as provides the scientific systematisation of problems related to fatigue life.

Assessment of the static strength of linear textile products

One of the methods of assessment of strength properties of yarns is based on tests carried out on strength testing machines (tensile testers). The results obtained allow for initial assessment of how a yarn tested will react during its processing into a flat textile product [23]. However, there is some risk that study results showed, which is often forgotten in the case of the assessment of strength properties of yarns in the context of trade, e.g. the values of breaking forces and elongations at break of yarn made on strength testing machines produced by different companies are not identical [17-20, 30]. This issue was raised by Konecki [29], among others

In European Union countries this type of research at present is conducted on the basis of requirements of the standard called PN-EN ISO 2062: 2009 Textiles – Yarns from packages – Determination of single-end breaking force and elongation at break using constant rate of extension (CRE) testers while before 2010 the standard PN-EN ISO 2062:1997 was obligatory. According to this standard, under arrangements between the parties concerned, also the use of testing machines using the constant rate of trawell (CRT) and constant rate of loading (CRL) systems can be used for assessment the breaking force and elongation at break of threads from packages.

As a result of studies, the following values are usually provided:
- Average breaking force in expressed in centinewtons (established with an accuracy of three significant figures),
- Average elongation at break expressed in percent (established with an accuracy of two significant figures),
- Coefficient of variation of the breaking force (established with an accuracy of 0.1%),
- Coefficient of variation of elongation at break, if it is required (established with an accuracy of 0.1%),
- Linear density of yarn tested, as a tex value (established with an accuracy of three significant figures),
- Breaking tenacity (specific strength), if it is required, expressed in centinewtons per tex (established with an accuracy of cN/tex).

In light of literature on the subject [5, 6, 9, 13 - 16, 42, 43], it can be concluded that the assessment of the static strength of yarns has been carried out using strength testing machines based on a constant rate of elongation (CRE). In the

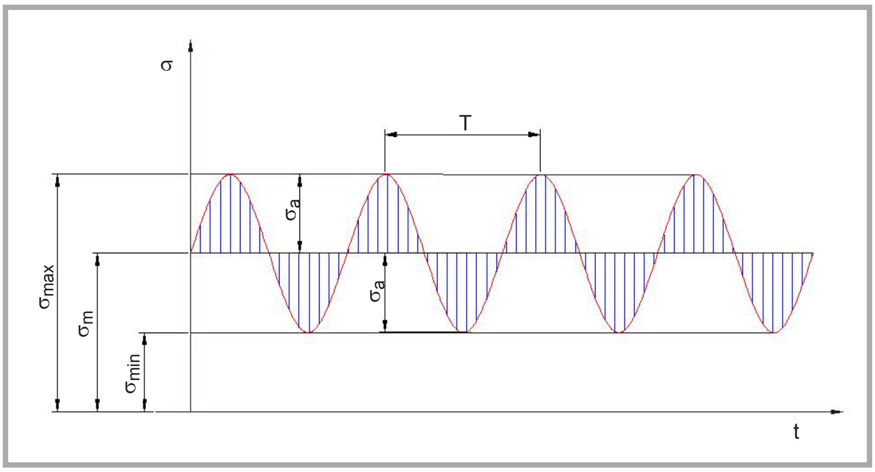


Figure 2. *Values characterizing stress cycles (based on [28]).*

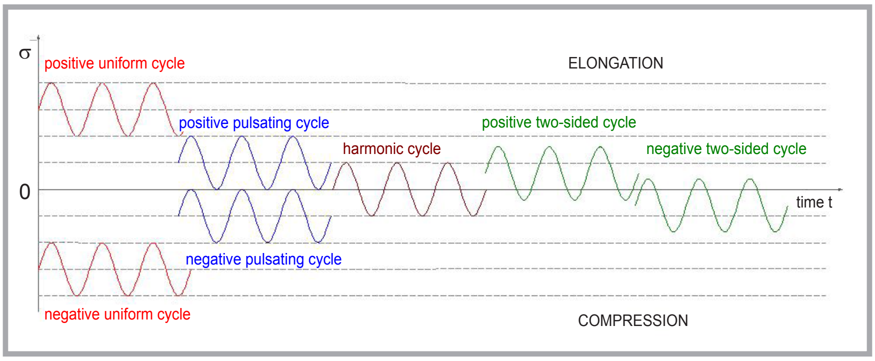


Figure 3. *Types of sinusoidal stress cycles [34].*

case of comparison of the breaking force in relation to yarns having specific distortion, e.g. connections of two broken endings of yarns, a reduction in fibre strength appeared. This issue was discussed by Frontczak-Wasiak, Snycerski [14 - 16] and Snycerski [42]. The authors assessed the static strength of connections of plaited yarns with the use of so-called connection efficiency. Drobina and Machnio [9], Cheng Lam [4 - 6], Drobina and Lewandowski [8] characterised the strength of plaited connections of endings of yarns using the coefficient of maintaining the strength of the connection defined as the quotient of the breaking force of the yarn that contained the connection and one without a connection. Similarly an assessment of the static strength might be considered in relation to yarns having programmable distortions of their structure in the form of various types of ornamental effects, such as flickers, for example.

Examining the quality of the said yarns from the point of view of the static strength is insufficient. According to Słodowy [41], the determination of classic indicators grading the yarn is based on specifying its strength parameters with the use of a tensile tester. Exclusively using indicators specifying only the static strength, just reflects the correctness of the production process of yarn, rather than predicting its future usefulness in processing, which may cause mistakes in predicting how yarn will react during further processing. Traditional strength qualitology is based exclusively on a static or quasistatic single test load of a yarn [41]

Fatigue strength of yarns

One of the most commonly observed forms of destruction of textile material is fatigue destruction, which has very serious consequences, as it is usually unexpected. The fatigue destruction of not only textile products occurs at a level of stresses which is much lower than in the case of the strength at break (temporary strength) [10 - 12, 26 - 28], or yield point. As previously mentioned, the level of these stresses depends on the type of material, the state of the surface as well as on technological processes of production. Fatigue destruction might be understood as destruction that has occurred at external loads variable over time. However, different types of loads and related properties of materials may be distinguished. In the case of static loads, where the force acting on a tested body is slowly changing over time, dynamic loads - violent (striking and impact), cyclic - fatigue as well as stable and long-lasting loads cause that the destruction of materials takes place in a way which is diverse, different and dependent on the prevailing conditions. Such changes might be regular and cyclic, e.g. in the form of sinusoidal loads:

$$F(t) = \sin(\omega t + \varphi), \qquad (1)$$

where, t - time, ω - circular frequency of load changes, φ - initial phase angle.

The time course of changes, called a stress or a load spectrum, is of a random nature (stochastic) in general. This is often a periodic process, i.e. cyclic and variable. In fatigue research, variable sinusoidal loads and stresses defined with a harmonic function are of great importance [3].

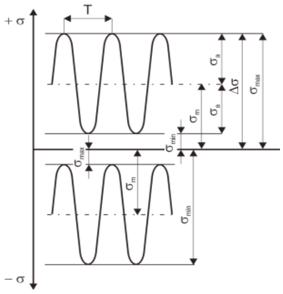
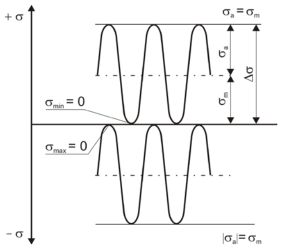
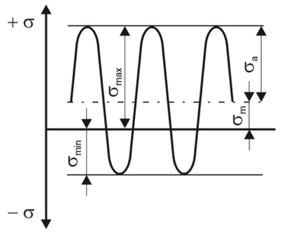
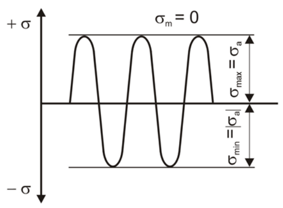
In practice, unsteady loads, resulting primarily from operating conditions, are the most frequent. In such cases we deal with fatigue destruction in vehicle elements, numerous types of structures as well as textile materials whose use is no longer limited to clothing. Because of the complexity of occurring phenomena and complicated mathematical description, the description at steady loads is often used.

It is extremely important to determine stresses below which fatigue destruction will not occur, or to determine the time in which there is a high probability of, for instance, damage at a given level of stresses. It is also worth emphasising differences between fatigue strength - Z, i.e. stresses below which there is no fatigue of a material, immediate fatigue strength - σ_N, i.e. the value of stresses for which the fatigue of a material will take place upon operating a specified number of cycles, e.g. 10^4, and the fatigue life - N, i.e. the number of cycles followed by the fatigue of a material for a given value of stresses.

The basic parameters of a variable sinusoidal cycle (***Figure 2***) are as follows:

- maximum stress - σ_{max},
- minimum stress - σ_{min},
- average stress - σ_m,
- amplitude - σ_a,

Table 1. *Selected cases of periodically variable states of stress;* ***Key to the table****:* σ_{max} *- maximum stress,* σ_{min} *- minimum stress,* σ_m *- average stress,* σ_a *- amplitude,* R_a *- asymmetry coefficient,* χ *- stability of load coefficient [28].*

No.	Cycle		Stresses			Coefficients	
			σ_{max} σ_{min}	σ_m	σ_a	R_a	χ
1	One-sided		$\sigma_{max} > 0$ $\sigma_{min} > 0$	> 0	≠ 0	$0 < R_a < +1$	$1 < \chi < +\infty$
2	One-sided negative		$\sigma_{max} < 0$ $\sigma_{min} < 0$	< 0	≠ 0	$+1 < R_a < +\infty$	$-\infty < \chi < -1$
3	Pulsating positive		$\sigma_{max} > 0$ $\sigma_{min} = 0$	1/2 σ_{max}	1/2 σ_{max}	0	1
4	Pulsating negative		$\sigma_{max} = 0$ $\sigma_{min} < 0$	1/2 σ_{min}	1/2 $\|\sigma_{min}\|$	$-\infty$	-1
5	Two-sided		$\sigma_{max} > 0$ $\sigma_{min} < 0$ $\sigma_{max} > \|\sigma_{min}\|$	> 0	≠ 0	$-1 < R_a < 0$	$0 < \chi < 1$
6			$\sigma_{max} > 0$ $\sigma_{min} < 0$ $\sigma_{max} < \|\sigma_{min}\|$	< 0	≠ 0	$-\infty < R_a < -1$	$-1 < \chi < 0$
7	Changeable		$\sigma_{max} = -\sigma_{min} > 0$ $\sigma_{min} < 0$	0	$\sigma_{max} = \|\sigma_{min}\|$	$\sigma_{max} = -\sigma_{min} > 0$ $\sigma_{min} < 0$	$\sigma_{max} = \|\sigma_{min}\|$

- stress cycle (period) - T and
- frequency - f_c [28].

The listed values are related to each other with the following dependencies:

- maximum stress - $\sigma_{max} = \sigma_m \pm \sigma_a$,
- minimum stress - $\sigma_{min} = \sigma_m \mp \sigma_a$,
- average stress - $\sigma_m = (\sigma_{max} + \sigma_{min})/2$, and
- amplitude (amplitude stress) - $\sigma_m = (\sigma_{max} - \sigma_{min})/2$.

In addition to the aforementioned values, two more coefficients are often applied, namely the asymmetry coefficient $R_a = \sigma_{min}/\sigma_{max}$ (sometimes called the amplitude coefficient of a cycle), and the stability of load coefficient $\chi = \sigma_m/\sigma_a$. The following dependencies take place among the said coefficients

$$R_a = (\chi - 1)/(\chi + 1) \text{ or}$$
$$\chi = (1 + R_a)/(1 + R_a).$$

In individual types of load cycles, the stresses may change their value, or value and sign. If maximum and minimum stresses have the same mark, we often talk about a one-sided positive or a one-sided negative cycle. A cycle in which one of the extreme main stresses is equal to zero is called a pulsating cycle. If $\sigma_{min} = 0$, then we deal with a positive pulsating cycle, whilst in the event when $\sigma_{max} = 0$, we determine a cycle as a negative pulsating cycle. A cycle in which maximum stresses are of a different mark is called a two-sided cycle [28]. A cycle in which $\sigma_m = 0$ is called a changeable cycle (symmetrical ***Figure 3*** presents different types of sinusoidally changeable stress cycles).

Table 1 lists cases of periodically variable states of stress based on the standard (PN-76/ H-04325 - "Basic definitions and general principles for preparation of samples and carrying out tests").

For textile materials, the primary source of information about fatigue properties of the material are the results ranked in a tabular form or Wöhler's diagram. This diagram allows to easily assign the fatigue strength of a material [28], which is obtained on the basis of a series of samples subjected to changeable stresses leading to destruction. Determination of the fatigue strength is carried out in such a way that stress is applied to samples in the following cycles: σ_m - average stress and σ_a - amplitude, until the material is destroyed at N cycles, or if the number of cycles exceeds the lim-

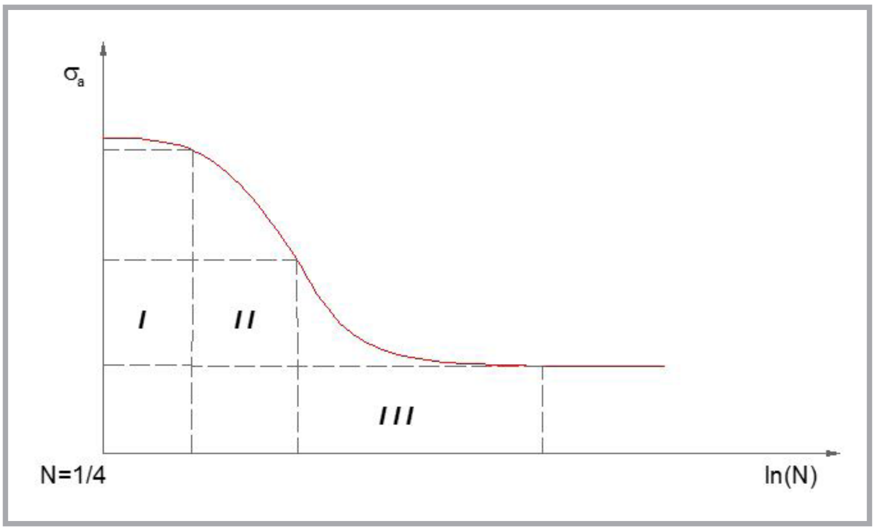


Figure 4. *A full Wöhler's diagram with marked areas of strength, I - quasistatic, II - low-cycle, III - high-cycle [28].*

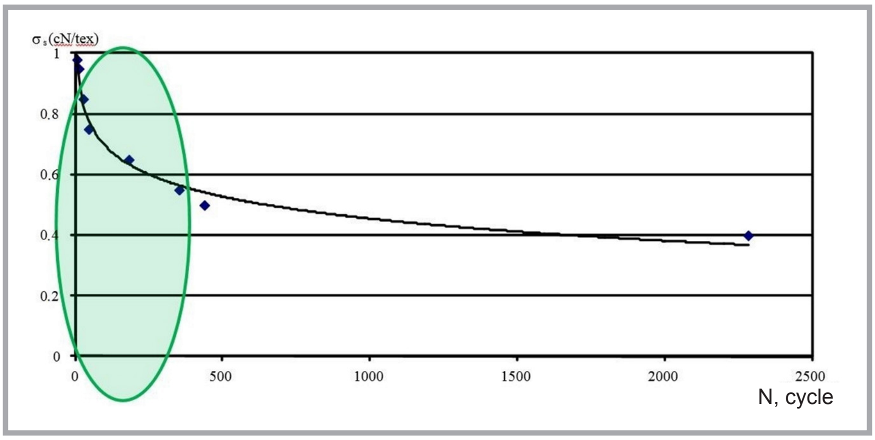


Figure 5. *Diagram of Wöhler's curve for cotton yarns smooth about the linear mass of 30 tex.*

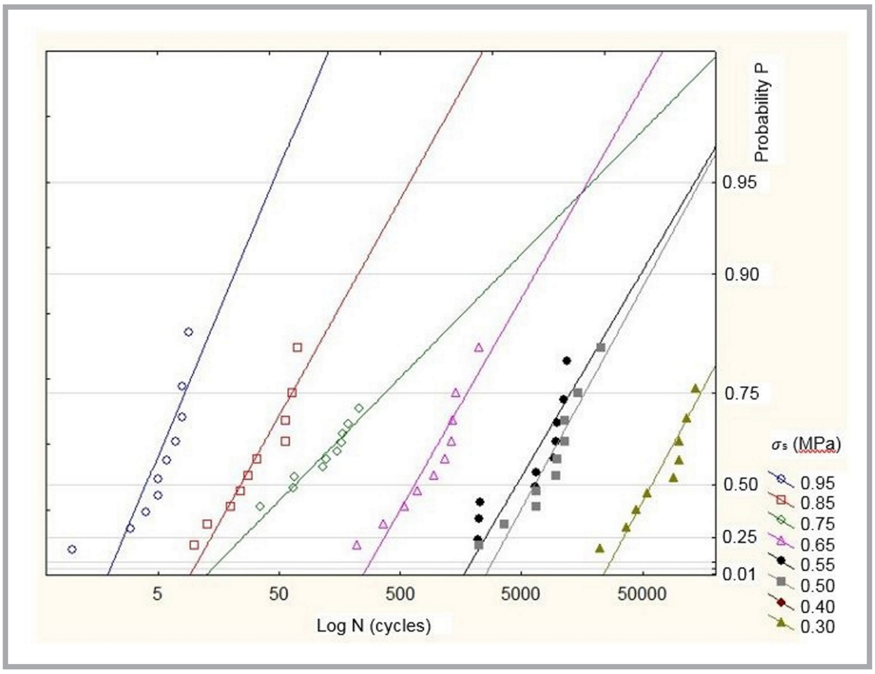


Figure 6. *Weibull's expansions of fatigue durability of knitted fabrics produced from standard smooth cotton of linear density 30 tex.*

ited number of cycles N_g adopted as the basis of fatigue tests. If a sample is damaged, we receive a specific value of a limited fatigue strength. In the case of the sample not being damaged, despite exceeding N_g, it means that the fatigue strength lies at higher values of σ_m & σ_a than those which had been planned in the studies of a given material. Each fatigue cycle is determined by σ_m & σ_a, which necessitates determining which of the parameters is going to be used in tests. In most cases, σ_m is constant and the influence of σ_a on the number of cycles required to damage a given material is studied. Measurements of material strength may be carried out for R_a = *const* or σ_{max} = *const*, especially in the case of a pulsating cycle. The most frequently used coordinate system is the semi-logarithmic system (σ_a, log$N$) or two-logarithmic system (logσ_a, log$N$); sometimes (σ_a, N) and (σ_a, l/N) are also used.

As previously mentioned, to assess the fatigue strength, Wöhler's diagram is most often used [24, 28]. Drawing a Wöhler's curve is quite difficult because the results obtained show quite considerable dispersions caused primarily by the lack of uniformity of the material of samples. Therefore the final form of the diagram should be developed on the basis of statistical calculations depending on the size of samples and the level of stresses [28]. ***Figure 4*** presents schematically a full Wöhler's diagram for zero pulsing stretching of samples of plastic material, e.g. steel and aluminum alloy. In the case of non-textile materials, the beginning of a cycle corresponds to 1/4 and it is assumed that destroying stresses shall be equal to the material strength R_m.

This diagram is made up of three areas [28]. Area I is defined as the area of quasistatic breaking or quasistatic strength. In areas II and III the destruction of elements takes place via an increase in changes or accumulation of fatigue damage. In area II, breaking occurs at high stresses and plastic deformations; this area is called one of low-cycle strength or a low-cycle fatigue. In area III, breaking occurs at lower stresses and vanishing plastic deformations. This area is referred to as high-cycle strength or a high-cycle fatigue. The Wöhler's diagram is often treated as the characteristics of a material in the scope of unlimited fatigue strength. Wöhler's diagrams allow to designate the fatigue strength for a given load cycle, while changing the value of the stability of load coefficient - χ we receive a number of diagrams of the same material. For a characteristic of fatigue properties in terms of asymmetrical loads, a diagram of stresses at a yield according to Haigh or Smith is created. ***Figure 5*** shows a full Wöhler's diagram for cotton yarn of linear density 30 tex.

In the case of fatigue tests of textile materials, a characteristic feature is the visible scope of low-cycle strength, which is often treated separately for non-textile materials. This range is identified with a short period of durability of an element or system. In the case of structural elements it might refer to large loads, causing high stresses, but they are rare. An example might be the overload of a plane chassis during take-off and landing. Machine design tests of non-textile materials in the scope of low-cycle fatigue have been initiated relatively recently, and therefore lots of problems have not been adequately explained yet, with some views possibly being controversial [3].

The tests of fatigue stress are carried out in such a way that each sample is subjected to a changing load at several fixed load levels. Then for each series of samples for a given load level, the N number of destructive cycles of load changes are determined. Instead of the number of cycles, its natural logarithm log N is often stated for results elaboration. In most cases, distribution of the N values are of log-normal distribution nature in the scope of limited fatigue strength. To make sure whether a set distribution is of a log-normal nature, one might use a so-called probability graph, in which the log N values are recorded on the x-axis and probability P is recorded on the y-axis. It is the so-called fatigue graph in probabilistic approach in P - log N coordinates for $\sigma_a = const.$

Figure 6 shows Weibull's distributions of the fatigue life of knitted material of cotton yarn of linear mass 30 tex.

Calculations of this type are extremely difficult as they require the use of numerical techniques. However, in the final stage, one receives data which enable further design of elements e.g. structural ones, which might be obtained by so-called censored studies [28], in which observations are usually tested at a specific time. For part of the observations at a specific time, no searched event, in this case damage, will be observed. It is known, however, that this event will occur sometime in the future. We call this right censoring. Left censoring occurs when we know that a given event has been observed before, but we do not know exactly when. For instance, we study when a given material will be damaged and when we will have to replace it with a new one. Censored studies (limited) of fatigue life, e.g. structural materials or machine parts are characterised by a significant reduction in the baseline number of cycles N. As a result, we get the opportunity to significantly reduce the studies as well as lower the number of positive attempts in a test. Censored studies also entail a reduction in the accuracy of the assessment of the fatigue life. Thanks to selecting an appropriate model of damage accumulation, the probability of accuracy of the results at a predetermined level might be, to some extent, obtained. However, in the initial phases of designing structural elements or textile materials, it is recommended to use fatigue life assessments covering a full study. Therefore in textile science, due to the lack of statistics devoted to given textile materials, full fatigue tests should be carried out in order to determine the limits of the fatigue strength. Nowadays the subject matter related to fatigue strength is of an interdisciplinary nature and covers also textile materials, which is reflected in such technological processes as weaving, knitting or the production of yarn.

As a result of a significant increase in the performance of looms, there is a significant rise in yarn stress during the process of weaving [1, 22]. In consequence, quality requirements for manufactured yarns has increased, especially with regard to their strength properties. The issues of the strength of yarns considered so far have discussed the variability of forces over time. In general the forces acting on the product change their values and sense over time. As experimental methods on the strength of material are developed, it has been observed that textile materials are often damaged at stresses which are much lower than the strength of a given material determined in certain static tests. Such damage (e.g. fractures) takes place without any observable plastic deformations, with the cause being, among others, an imperfect elasticity of the material [3, 7, 21, 35, 37, 48, 51, 52].

The issue of the life of polymers has been the subject of intensive research since the fifties of the 20th century. The first works in this field were published by Zhurkov [38] as well as Zhurkov and Tomaszewskij [57], who formulated a kinetic theory of the strength of materials. This issue was further developed by Zhurkov and Sanfirow [56], Lieksowskij and Regel [33], Regel [39] and Bartniew (Regel, Słucker, Tomaszewskij [40]), Bartniew and Tulino [2]. Włochowicz and Linek [53] suggested a new look at the theory of Zhurkov in their thesis entitled „Application of the Zhurkov - Abasov theory for description the strength properties of polyethylene teraphtalate fibres". Włochowicz and Linek [53] presented a modified equation by Zhurkov which expanded the limits of its use by materials characterised by the flow during stretching. For these materials, the structural factor γ depends on the speed of stretching and temperature, resulting in a loss of material strength with increasing speed at large values and much higher influence of the temperature on strength than was assumed by Zhurkov. In addition, the authors in [53] took into account the effect of intermolecular bonds on stress in a material, which are responsible for a linear decrease in the activation of the destruction process at the time of raising the temperature. The analysis of Zhurkov's theory was confirmed by the results of tests which had been carried out on polyester fibres with a low-orientation degree. Particular attention should be given to the works of Włochowicz and Nowak [52] as well as Nowak and Włochowicz [37]. The authors investigated the physical microstructure of samples made of polyamide 6 (Ternamid T-26) using the method of injection of different mechanical loading and thermal loading coupled with it as well as the influence of the conditions of moulding and thermal treatment on the structural and mechanical properties of a material. The authors found that the process of mechanical fatigue of a material covers the areas that have the most properly developed lattice. The Wöhler's curves presented allowed to determine the fatigue life of samples made by injecting plastic into a warm mould and of samples produced with a different technology. As a result of an analysis of the Wöhler's curves carried out, Włochowicz and Nowak [51, 52] as well as Nowak and Włochowicz [37] found that the fatigue strength is also affected by the type of thermal treatment and time of relaxation applied in the appropriate climatic conditions.

According to Urbańczyk [45 - 47], the fatigue strength of fibres depends significantly on their physical state, i.e. temperature and humidity. Especially assessment of the fatigue strength of fibres is also influenced by various instrumental measurement parameters, such as:
1. Frequency of load cycles.
2. Amplitude of a load cycle.
3. Nature of changes in the load applied or elongation forced in a cycle.

The frequency of given cycles is determined by the total duration of a full load cycle, and thus by the duration of the offload and rest. Increasing the time of the load, and particularly the rest, makes it possible to relax internal stresses more fully, and hence reduce energy which is permanently accumulated in one cycle. This leads directly to an increase in the number of load cycles which a fibre can endure. Therefore it might be said that an increase in the frequency of cycles results in undervaluation of the destructive cycle indicator - N_d.

The periodisation of the stress cycle is understood by the author as the division of the overall cycle time into the load, offload and rest stages. The periodisation of a cycle might varies within quite wide limits. Urbańczyk [45 - 47] states that by increasing the cycle time dedicated to the rest of a sample, a more complete relaxation of internal stresses is achieved, which in turn will lead to an increase in the value of indicator N_d.

As the third instrumental parameter of measurement affecting the result obtained, he indicates the nature of stress changes or elongation in a load cycle. Instruments used for the fatigue testing of stretching, so-called pulsators, may be designed in a way to provide the elongation of a sample in accordance with a specific programme. The possibilities of programming are quite extensive.

The most commonly used variants of studies are systems in which the stability of force amplitude or tensile stress, or constant amplitude of forced elongation of a sample are provided in successive load cycles.

Jurasz [47] discussed the problems of assessing the fatigue attribute as well as finding appropriate indicators characterising the technological usefulness of yarns. According to the author in [25], the internal destruction of threads causes changes in the parameters of a model and their stretching, i.e. Young's modulus and viscosity. These parameters determine the mechanical properties of a thread. In this sense, all parameters that define a stress curve of threads might be measures of the internal destruction of threads [25]. The issue of the technological usefulness of yarn was also discussed by Słodowy [41]. The essential problem with creating comprehensive indices according to the author in [41] is to define the parameters of enforcement which are the representatives for a given process.

So far, laboratory valuation methods used for assessment of threads have allowed for selective predicting of their reaction to specific enforcements [41]. However, they do not reflect the details of a technological process. Considering the complexity of configuration of impacts on a thread in a technological process, the statement adopted is that only indicators obtained in the process of its implementation may properly characterise the technological usefulness of threads. Hence indicators of breakage of threads, efficiency of the process and quality of the product obtained are commonly referred to.

Słodowy [41] states that one of the unconventional methods for estimating the usefulness of yarn for certain textile processes was one on the basis of the WIRA concept [50]. This method was based on step-like putting of a thread unwound from a beam through an area of growing load, recording the number of breaks in its individual zones, and then analysing the distribution of values derived. At times when the requirements for yarn were much lower, and the performance of a machine incomparably lower, this method was useful. According to Słodowy [41], finding new methods of assessing the technological usefulness of yarn is very important. Referring to the WIRA concept, a research procedure which revealed the weaknesses of yarn was developed at the Institute of Mechanical Technology of Lodz University of Technology. Simultaneous abrasion and elongation of yarn disturbs its structure in a way which is typical for textile processes. This method allows to specify the degree of decreasing strength of a thread at a given fatigue. A new feature of a thread which could not be determined with the use of traditional methods of research is extracted in this way.

The laboratory loom method, used to determine the usability of a given yarn in the weaving process, has been known for a long time. This observation was the basis for classifying a given yarn as more or less useful for processing in a weaving plant. According to Słodowy [41], the answer to the question regarding the reason for breakage cannot be found with the use of this method. The author concludes that a method using an abrasive and stretching enforcement generator in conjunction with a method making use of a dynamic pulsator leads to showing specific fatigue features, which enables their identification, and not just information about crossing the line of the extensively understood strength of a thread, as is in the example of a laboratory loom [41].

Issues related to the fatigue properties of yarns were also discussed by Radivojevic, Stairjenkovic, Stepanovic and Trajkovic [38]. The subject of their research was wool worsted yarns. These authors analysed fast-changing deformations of yarns in the process of creating a winder beam from cops. During the research, authors Radivojevic, Stairjenkovic, Stepanovic and Trajkovic [38] applied a value of elongation of the warp, which imitated the process of weaving. The purpose of their study was to estimate the stresses of yarn produced in different conditions of rewinding and to investigate polycyclic mechanical characteristics of yarns which are significant for further technological processes, as well as important for determining the quality and predicting their reaction in later textile processes. In their work, Radivojevic, Stairjenkovic, Stepanovic and Trajkovic [38] applied a method developed by Kukin, Solovjev and Koblakov [31], used to determine fatigue characteristics. On the basis of the analysis carried out, they found that in the first ten cycles of stretching yarn, the largest deformation and mechanical losses appear. With each new cycle, as a result of the extension of the yarn, structural elements of the yarn move, causing the drawing aside of such elements, which in turn leads to the weakening of ties among them. Radivojevic, Stairjenkovic, Stepanovic and Trajkovic [38] suggest that an increase in yarn stress during the process of rewinding causes the faster fatigue of yarn while performing the load-offload cycles, which is highlighted by an increase of deformation, a reduction in yarn resistance to circular deformation of stable elongation, and a decrease in mechanical losses. The issue of polycyclic loads during the process of weaving was discussed by Vangheluve [48], who claimed that when stopping the loom, the warp threads are exposed to dynamic loads. Vangheluve [48] proposed her research method based on the fact that after a fixed number of load cycles, the measurement of relaxation at fixed elongation was performed. As for determining measuring ranges for load - offload, the author has not justified the criteria adopted. The only premise in her deliberations was referring to the visco-elastic properties of yarns subject to Maxwell's model. In addition, Vangheluve [48] presented a simulation of the process of relaxation of warp yarn at a time of stopping the loom. They found that the relaxation of warp yarns in the process of weaving influences the occurrence of numerous errors.

Based on the literature, it can be concluded that the most effective method of measuring the fatigue and dynamic properties of yarn is still being searched for. The methods used nowadays are experimental and not covered by any standards. Experimentally the life of samples is assessed on pulsators or special strength testing machines. Tumajer, Ursíny, Bílek and Moučková [44] carried out an assessment of fatigue strength for two types of fast-changing and impact tests. To describe the dynamic properties, they applied the Laplace transform. VidTex - a special device for dynamic research was presented in the experimental part, including the possibility of its use. However, due to the fact that pulsators operate according to various rules of operation, the results obtained with one device cannot be directly compared with those obtained in other cases. Also the use of such results to describe the quality of semi-finished products and articles requires critical analysis.

The issue related to the fatigue strength of yarns was also discussed by Frontczak-Wasiak and Snycerski [14, 15]. To assess the fatigue properties, the authors applied a pulsator which imitated elongation cycles corresponding to the number of fatigue cycles of a basic part of the warp of a Wilton loom. Frontczak-Wasiak and Snycerski [14, 15] as well as Włodarczyk and Kowalski [54] also studied the resistance to abrasion as a result of contact with the friction barriers of a loom. According to Frontczak-Wasiak and Snycerski [14, 15], the use of this type of research mostly reflected the conditions to which yarns with plaited connections are subjected. On the basis of the studies made, Frontczak-Wasiak and Snycerski [14, 15] claimed that the results of plaiting as well as the strength properties of a connection may depend on the accidental properties of a yarn in the place of connection, as the yarn used for studies was characterized by a large degree of irregularity.

Nosraty, Ali Jeddi and Jamshidi Avanaki [36] conducted an analysis of the overall characteristics of three filament yarns, i.e. polyester, polypropylene and polyamide (nylon). The fatigue reaction of these yarns was subjected to load simulation with the use of a pulsator in the frequency range of 5 and 20 Hz. In the course of carrying out the simulation of fatigue loads, significant changes in parameters relating to the elongation, stress of yarn, the real part of a complex modulus of a yarn as well as the loss modulus and damping factor were recorded.

The results in [36] of studies proved that PP yarns showed minimal change in their mechanical reaction, and yarns made of nylon had the lowest characteristics at various conditions of loading of samples. It was found that the resistance of nylon yarns to cyclic loads was higher than in the case of PP and PET yarns. In addition, polyester yarn turned to be the weakest due to a larger range of changes in their mechanical and physical properties.

In the light of the literature review, it can be concluded that the subject matter related to assessment of the fatigue life of linear textile products has not been fully identified. There is a lack of reports on methodology of carrying out research. The issue related to the assessment of fatigue strength and development of appropriate probabilistic models is worth deeper analysis.

Summary

The thesis contains comments on the fatigue strength research of textile materials. It constitutes the broadening and complementing of existing knowledge related mainly to the fatigue analysis of structural materials, such as steels and non-ferrous metal alloys.

Analysing the issues presented, it might be noted that the problem of the fatigue strength of linear textile products is very important for manufacturing and use of finished products. Understanding the fatigue strength of textile products is therefore significant not only from a theoretical and cognitive point of view but also from a utilitarian point of view, which is particularly vital in the case of products intended for technical articles (tire cords, force belts, conveyors, etc.).

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